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Reverse osmosis alternative: Energy implication for sugar industry

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Abstract

In classical sugar factories, evaporation is one of the most energy intensive unit operations which mainly used for concentrating thin sugar juice. Replacing or combining this process with low energy consuming processes such as membranes could save large amounts of energy. There is no phase change in common membrane technologies and therefore they are low energy consumers. In the present study, a two-stage reverse osmosis system was investigated for pre-concentrating the sugar syrup. The energy consumption was compared for conventional evaporation versus reverse osmosis combined with evaporation. The obtained results represented several benefits such as significant energy saving and no thermal loss of sugar using the RO system.

Keywords: Energy saving; Reverse osmosis; Evaporation; Sugar

1. Introduction

Evaporation is an energy intensive process in sugar factories. After filtration of sugar thin juice, the feed enters into the multi-effect evaporators with around 15% sugar. Brix degree is defined as the percent of dry substance in a solution. The brix degree of the concentrated sugar solution is more than 60. Due to the high latent heat, evaporation of water consumes huge amount of thermal energy and fuel which results in higher operating costs and environmental problems. Furthermore, heating sugar juice could lower the product quality by changing the color and flavor.

Finding low energy consuming alternative processes have been of scientists' interest. Membrane processes with no phase inversion could be considered as the best candidates for this purpose. These processes are very energy effective and could replace current energy intensive processes like evaporation and distillation solely or in hybrid configuration.

Dehydration of sugar solutions is one of the capabilities of membranes. Some of the membrane processes such as membrane distillation [1], osmotic distillation [2–7], nanofiltration [8–11] and reverse osmosis could be applied to sugar syrup concentration. The possibility of employing reverse osmosis in sugar industry is subject of researches from several years ago [12]. In a paper by Bichsel and Sondre [13], concentrating sugar thin juice from 13–30% of sugar content is studied using PA300 and FT30 reverse osmosis membranes. The benefits and advantages of membrane technology over common evaporation including lower cost are clearly shown. UF-RO combined systems are also investigated in some literatures for thin juice concentration purpose [14,15]. Kiss et al. [16] compared a MF-RO-NF membrane system with evaporation in must production. Saska et al. [10] applied RO and NF membranes for concentration and decolorization of dilute products from cane molasses desugarization for direct production of white sugar. Hogan et al. [4] reported that a hybrid process involving pre-concentration of the feed by RO followed by further concentrating the RO retentate by osmotic distillation, could yield a highly concentrated product of an excellent quality, but at significant reduction in processing cost. For instance, this reduces the evaporator capacity requirements by one-half.

The application of several commercial reverse osmosis membranes in different operating pressures were studied for sugar concentration in a previous work [17] by our research team. BW30 reverse osmosis membrane at 22 bar showed the best performance for concentrating sugar thin juice. The comparison of the energy consumption for this membrane as a

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pre-concentration step versus evaporation is investigated in the present study.

2. Materials and methods

2.1. Experimental setup

The schematic of the bench-scale cross-flow apparatus which we used in the experiments is shown in Fig. 1. The membrane process was a batch concentration, i.e. the permeate stream was taken out and the concentrate stream was returned to the feed tank. The reciprocating feed pump provides required high-pressure feed stream. Its maximum safe temperature and pressure was $T_{max} = 50\,°C$ and $P_{max} = 110$ bar, respectively. High-pressure hoses were used for connecting different parts of the system. The applied pressure was controlled using two valves on bypass and concentrated streams. Indeed these valves were used to adjust the flow rate and operating pressure in the membrane cell.

Two brass cubic parts made the membrane cell (Fig. 2). The RO membrane with an area of $0.0023\,m^2$ was fixed between the two parts. A perforated metallic layer was used as the membrane support which protects it against deformation and displacement. There was also a rectangular O-ring around the membrane site for sealing purposes. Two pressure gauges (0–60 bar) were placed before and after the membrane cell to monitor the applied pressure and the pressure drop.

2.2. Membrane

The BW30 reverse osmosis membrane manufactured by DOW with the general trademark of FILMTEC was used in all the experiments. BW (Brackish Water) membranes are usually used for water desalination purposes. This membrane is a commercial composite membrane with two layers and a smooth surface. The top layer and the support materials are polyethylene terephtalate and bisphenol A polysulfone, respectively. The skin material nature makes this membrane hydrophobic. The thickness of BW30 membranes is about 150 μm. The maximum operating temperature of Filmtec modules is 45 °C [18].

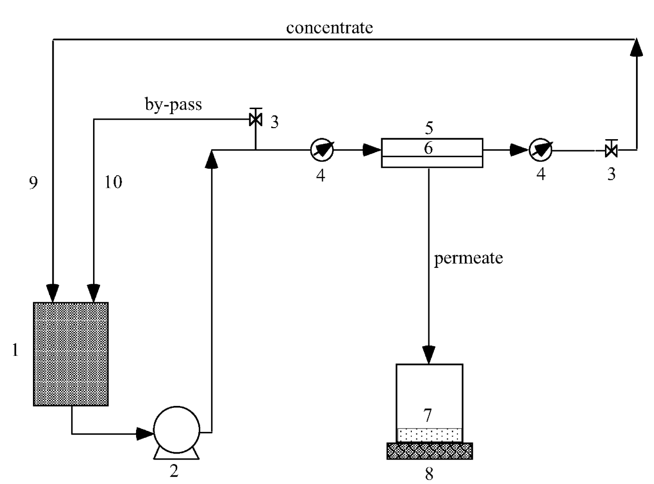

Fig. 1. Experimental set-up. (1) Feed tank; (2) pump; (3) valve; (4) pressure gauge; (5) crossflow cell; (6) membrane; (7) permeate; (8) balance; (9) concentrate; (10) by-pass.

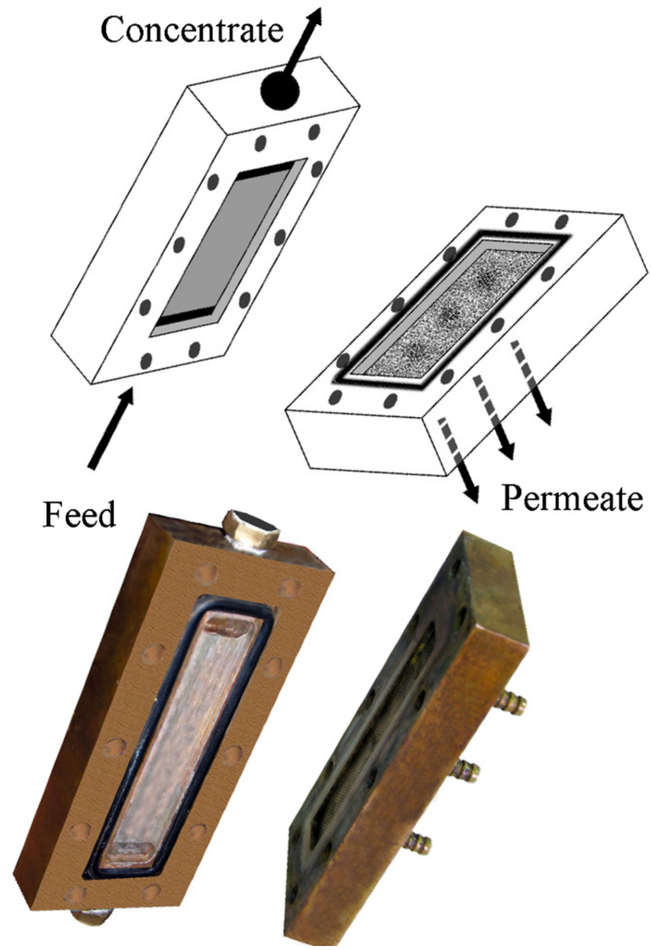

Fig. 2. Two cubic parts of the membrane cell.

2.3. Filtration procedure

About 10 l of thin juice were used as the feed in the experiments. The feed was directly pulled out from the manufacturing process, i.e. just before the evaporation step.

This juice is the direct product of filtration process in the factory with the brix degree of around 15 which should be evaporated and concentrated in evaporators. The feed was cooled down from 80–30 °C to protect the membrane and the pump against overheating during the operation. The operating temperature was between 30 and 45 °C during the experiments. As stated before the transmembrane pressure was set on 22 bar.

A rectangular piece of membrane was cut out and soaked in a 50% solution of water and ethanol before the experiment. The membrane is converted into hydrophilic after 10–15 min. Therefore, the experiments were carried out using a hydrophilic membrane indeed.

The permeate flux calculated from the permeate volume in the specified time intervals. There is a linear relationship between the brix degree and the sugar concentration. The brix degree of the feed and the permeated water were measured using a refrac-

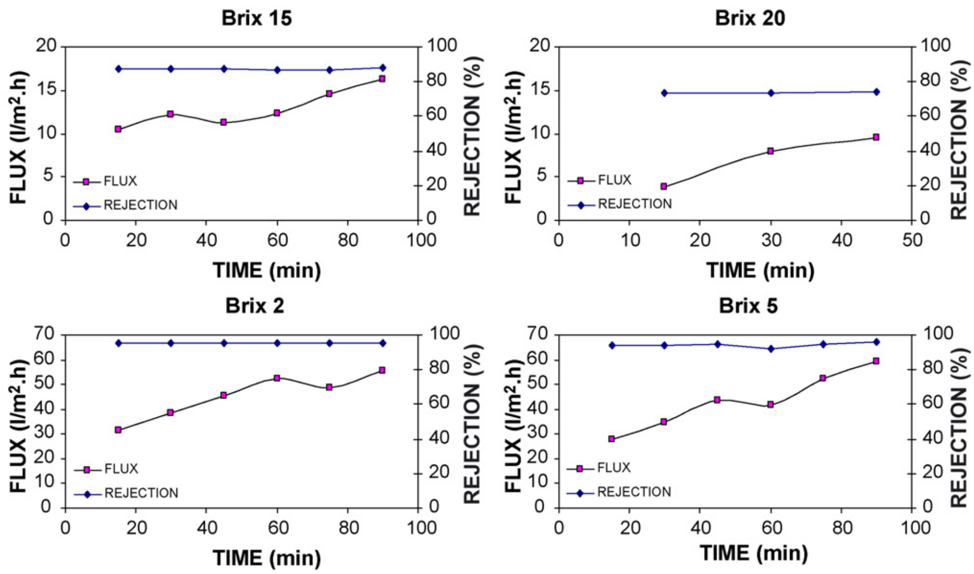

Fig. 3. Fluxes and rejections obtained in the experiments under 22 bar transmembrane pressure.

tometer with the accuracy of about 0.1–0.2° brix. Note that due to the low flow rate of permeate stream and high volume of feed, the sugar concentration of feed solution was almost unchanged. The rejection of sugar by the membrane was calculated as follows:

$$R = \left(\frac{1 - Bx_{\mathrm{P}}}{Bx_{\mathrm{F}}}\right) \times 100 \tag{1}$$

where R is rejection (%), Bx is brix degree and P and F subscripts are permeate and feed, respectively. The experiments were carried out with a feed of brix 15° as well as 20°. The permeate contains low sugar content. So a second stage was applied to achieve a sugar free permeate. Fluxes and rejections were calculated for all the experiments.

3. Results and discussion

The calculated fluxes and rejections under 22 bar transmembrane pressure are represented in Fig. 3. It is expected that rejections are higher for lower concentrations and nearly constant for each concentration. At higher concentrations, the concentration polarization phenomenon results in lower rejections and lower fluxes. Increasing trend for flux is due to the temperature increment during the experiments (about 15 °C) which was a limitation in our apparatus. Furthermore, the temperature rise has no important effect in the results. An average flux for each brix degree of feed was calculated. Finally an overall flux (an average over different brix degrees, temperatures, times, etc.) was obtained. There was no need to control the temperature in this range to obtain a unique approximated flux for each stage.

The energy consumption is calculated based on the average flux. Minimum efficiency and maximum energy consumption for membrane system is considered in whole calculations. The feed side pressure which should be higher than the osmotic pressure (Fig. 4) [19] is more than 22 bar to provide the sufficient transmembrane pressure.

Fig. 5 represents a general schematic of the two-stage process. The sugar juice flow rate into the evaporators in a typical beet sugar factory (e.g. Bisotoun Sugar Factory – Kermanshah, Iran) is about 80 m^3/h which should be processed through the membrane system first. The main concentrate stream (first stage) has a brix of 20° while the brix of second stage concentrate stream is 15° which is recycled to the main feed. Based on the obtained results, the first stage permeate flux was considered to be 10 l/m^2 h with brix degree of 4 which is fed into the second stage. These values are 20 l/m^2 h and 1°, respectively, for the second stage. Note that the permeate brix degree for a feed with brix degree equals to 2–5 is about 0.2–0.3 which could be considered as the pure water due to the refractomrter accuracy.

3.1. Membrane arrangement

An overview of the membrane arrangement is shown in Fig. 6. In this arrangement which is like a "Christmas tree", dilute feed

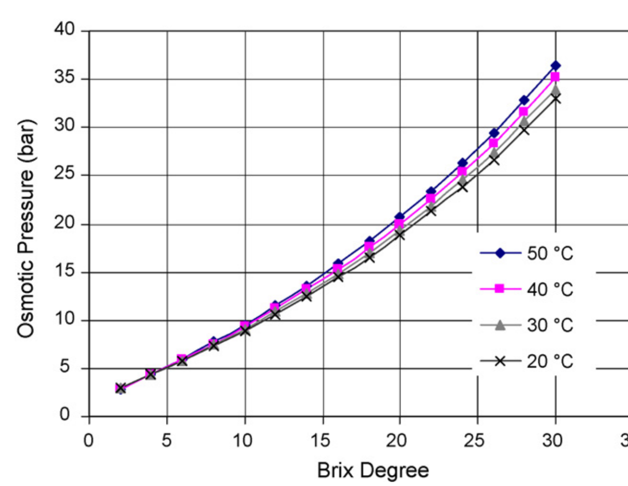

Fig. 4. Osmotic pressure of sugar juice vs. brix degree at different temperatures [19].

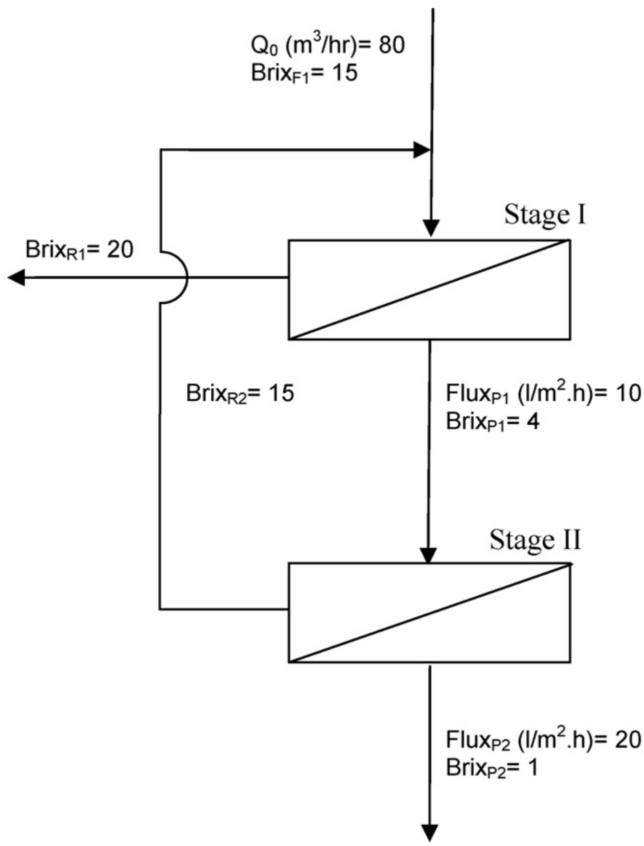

Fig. 5. General schematic of the two-stage membrane process.

is pumped into the first stage with a pressure more than experimental pressure. Due to the pressure drops the operating pressure considered to be 28 bar. The feed is distributed between the first set of parallel modules. The concentrate of the first set which its volume is less than the main feed, is fed to the second set of parallel modules. Therefore, the second set consists of fewer modules than the first set. We considered three sets of parallel modules in each stage. The final concentrate of the first stage is the concentrated product and the permeates of the first stage modules was fed into the second stage.

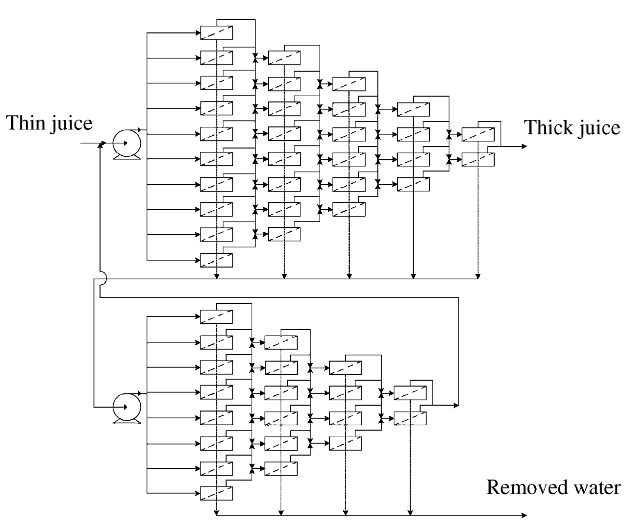

Fig. 6. A sample overview of the membrane arrangement.

The overall arrangement of the second stage is the same as the first. But the total number of modules and the number of modules in parallel sets are different. The second stage concentrated stream is recycled to the first stage feed and the permeated water of all modules leaves the system.

3.2. Membrane area and energy calculations

The juice flow rate and the required membrane area calculated using a material balance on sugar and water. We used the following equation to convert volume and mass. This approximation is the relation between specific gravity and brix degree at 20 °C [20]:

$$SG = 0.00425Bx + 0.9988 \tag{2}$$

The required membrane areas are calculated as 2801 m^2 and 1114 m^2 for stage one and two, respectively. Filmtec^{TM} BW30–400 standard spiral wound modules have an active area of 400 ft^2 (37 m^2). Therefore, using these modules we need 76 and 31 modules for the first and second stages, respectively [18]. The maximum feed flow of these modules is 19 m^3/h (5.3 l/s). We considered the feed flow rate of each module to be 3 l/s. The specifications of the membrane system are presented in Table 1. For example, the first stage consists of three sets of parallel modules with 48, 20 and 8 modules in each one.

Almost the only energy consumers in RO system are high-pressure pumps. The typical efficiency of high-pressure piston pumps varies from 50% in small ones to 90% in bigger pumps [21]. We assumed the efficiency of the pumps to be at the lower limit i.e. 50%. The following equation could be used to calculate the pump required power:

$$W = \frac{Q\Delta P}{\eta} \tag{3}$$

where W is the power (W), Q is the flow rate (m^3/s), ΔP is the pressure difference (Pa), and η is the efficiency of the pump.

A four-effect evaporator was considered for comparison with the membrane process. In the classical concentration, evaporator concentrates sugar thin juice from brix 15–60°. But in the hybrid process it should concentrate the product of RO system with brix 20° to the final brix of 60°. In an N-effect evaporator, each kilogram of steam could evaporate N kilogram of water approximately. The evaporated water in the concentration process and then the required steam could be calculated with a sugar mass balance. The input steam is at 137 °C and 2.5 bar pressure in the Bisotoun sugar factory. In these conditions the latent heat of water evaporation is assumed to be about 2200 kJ/kg. The minimum required energy, i.e. without respect to the real energy

Table 1
Specifications of the membrane system

Stage	First	Second
Membrane area (m^2)	2801	1114
Number of modules	76	31
Modules arrangement	48 + 20 + 8	20 + 8 + 3

Table 2
Energy consumption comparison between reverse osmosis and evaporation

	Energy consumption (kW)	Energy saving (%)
RO + evaporator	177 + 6376 = 6553	33
Evaporator	9740	

consumption of boilers, ancillary equipments, pumps etc., could be calculated based on the following equation:

$$q = m_S\lambda \quad (4)$$

where q is the thermal power (kW), m_s is the mass flow rate of the steam (kg/s) and λ is the latent heat of water evaporation (kJ/kg). The total energy consumption of the four-effect evaporator and the hybrid RO-evaporator process is calculated and represented in Table 2. Obviously, a huge amount of energy could be saved by applying membrane system for pre-concentrating the sugar juice. Calculating the required energy shows a 33% reduction in energy consumption of the concentration process using the RO system. Furthermore, using energy recovery systems like Pelton wheel and Turbo charger to exploit final high-pressure product, may result in higher energy saving [22].

The only disadvantage of RO is that evaporation separates water without any sugar loss through evaporated water, but the permeated water could have small sugar content. However, there are several solutions for this problem in RO system. The final permeate stream of the second stage could be recycled to the diffusion section of the plant and used for extracting sugar from beet peels. Another possible solution is employing a third stage in the membrane system. Due to the experimental results and BW30 membrane capabilities this stage could reject the remained sugar and provide pure water. Furthermore, the required membrane area of the third stage will be minor due to the low sugar concentration and flow rate of the feed and high permeate flux. The membranes stability and durability will be more and the fouling phenomenon is less and so this stage will not increase the process expenditures significantly. The third solution is dividing the permeate stream of the second stage to two or more streams. Because of the wide range of feed concentration in the second stage (brix 4–15°), the permeates of the first modules are more pure compared to the last ones. Therefore, we can use this water as the pure water and return the permeates of the last modules to the diffusion section.

4. Conclusions

In this study, a two-stage RO system was evaluated for pre-concentration of sugar thin juice and the energy consumption was investigated. Calculations showed a significant energy saving of 33% using this system to increase the brix degree of the thin juice from 15–20° prior to final concentration in evaporators. The final permeate sugar content is not zero but is negligible. Furthermore, there are solutions for this problem such as using the final permeate in diffusion section or applying a third membrane stage.

This work may be considered as the beginning of a comprehensive research needed before consideration of the application of this technique in the real industrial world. We aimed to show that a huge reduction in energy consumption is expected by employing the reverse osmosis process in combination with evaporation. Much comprehensive study such as consideration of concentration polarization, fouling reduction, viscosity increment, membrane cleaning, etc. is required before any final conclusion regarding the applicability of this technique in industrial scale.

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